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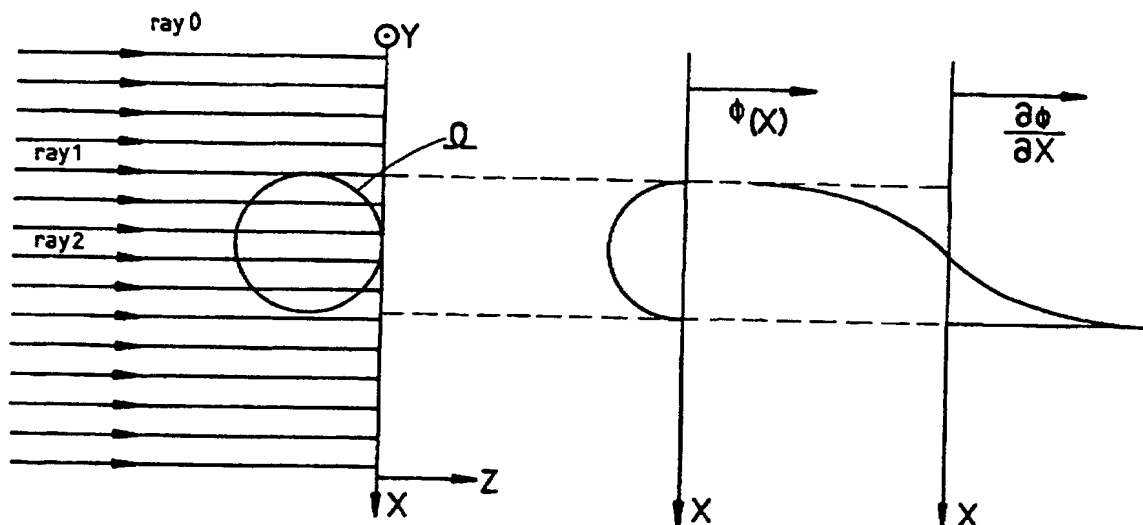


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(57) Abstract

A method of obtaining an image of a boundary of an object, the boundary representing a refractive index variation, the method including irradiating the boundary with penetrating radiation having high lateral spatial coherence and a propagation component transverse to the refraction index variation, and receiving at least a portion of the radiation on an image plane so as to form the image, the radiation having been refracted by the boundary such that the boundary is represented on the image by a corresponding intensity variation.

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5                   **SIMPLIFIED CONDITIONS AND CONFIGURATIONS FOR  
                    PHASE-CONTRAST IMAGING WITH HARD X-RAYS**

                    This invention relates generally to the observation of a structural feature of an  
                    object utilising penetrating radiation such as x-rays. More particularly, but not  
10                   exclusively, the invention relates to x-ray phase-contrast recordal, e.g. imaging, of  
                    internal boundary features.

                    The present applicant's international patent publication WO95/05725  
                    (PCT/AU94/00480) and provisional patent application PN5811/95 disclose various  
15                   configurations and conditions suitable for differential phase-contrast imaging using hard  
                    x-rays. Other disclosures are to be found in Soviet patent 1402871 and in U.S. patent  
                    5319694. It is desired that relatively simpler conditions and configurations more closely  
                    related, at least in some embodiments, to traditional methods of absorption-contrast  
                    radiography, may be utilised for differential phase-contrast imaging with hard x-rays.

20

                    In accordance with the present invention there is provided a method of obtaining  
                    an image of a boundary of an object, said boundary representing a refractive index  
                    variation, said method including:

                    irradiating said boundary with penetrating radiation having high lateral spatial  
25                   coherence and a propagation component transverse to said refraction index variation; and  
                    receiving at least a portion of said radiation on an image plane so as to form said  
                    image, said radiation having been refracted by said boundary such that said boundary  
                    is represented on said image by a corresponding intensity variation.

30                   The present invention further provides an apparatus for obtaining an image of a  
                    boundary of an object, said boundary representing a refractive index variation, said  
                    apparatus including:

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a source for irradiating said boundary with penetrating radiation having high lateral spatial coherence and a propagation component transverse to said refraction index variation; and

5 a detector for receiving at least a portion of said radiation so as to form said image, said radiation having been refracted by said boundary such that said boundary is represented on said image by a corresponding intensity variation.

The present invention also provides a method of deriving a phase-contrast record of an internal boundary having a sharp refractive index variation or defined by a  
10 thickness variation, comprising:

irradiating the boundary with penetrating radiation having a propagation direction such that there is a significant component of the propagation vector transverse to the direction of said refractive index variation or in the direction of said thickness variation, and further having a lateral spatial coherence sufficiently high for the variation in  
15 refractive index or thickness to cause a detectable change in the local direction of propagation of the radiation wavefront at the boundary; and

detecting and recording at least a portion of said radiation after it has traversed said boundary in a manner whereby an effect of said change in the local direction of propagation is observable and thereby recorded as a local diminution or rapid variation  
20 of intensity of the radiation which thereby substantially images the boundary.

The present invention further provides an apparatus for deriving a phase-contrast record of an internal boundary having a sharp refractive index variation or defined by a thickness variation, comprising:

25 means to irradiate the boundary with x-ray radiation having a propagation direction such that there is a significant component of the propagation vector transverse to the direction of said refractive index variation or in the direction of said thickness variation, and further having a lateral spatial coherence sufficiently high for the variation in refractive index or thickness to cause a detectable change in the local direction of  
30 propagation of the radiation wavefront at the boundary; and

means to detect and record at least a portion of said radiation after it has traversed said boundary in a manner whereby an effect of said change in the local

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direction of propagation is observable and thereby recorded as a local diminution or rapid variation of intensity of the radiation which thereby substantially images the boundary.

5       The present invention also provides a method of obtaining an image of a boundary of an object, said boundary representing a refractive index variation, said method including:

          irradiating said boundary with penetrating radiation having high lateral spatial coherence and a propagation component transverse to said refraction index variation; and  
10       receiving at least a portion of said radiation on an image plane so as to form said image, said radiation having been Fresnel diffracted by said boundary such that said boundary is represented on said image by a corresponding intensity variation.

          The present invention further provides an apparatus for obtaining an image of a  
15       boundary of an object, said boundary representing a refractive index variation, said apparatus including:

          a source for irradiating said boundary with penetrating radiation having high lateral spatial coherence and a propagation component transverse to said refraction index variation; and  
20       a detector for receiving at least a portion of said radiation so as to form said image, said radiation having been Fresnel diffracted by said boundary such that said boundary is represented on said image by a corresponding intensity variation.

          The present invention also provides a method of determining the phase of an  
25       image, including processing phase-contrast image data of said image.

          The intensity effect of a change in the local direction of propagation is preferably observable in an image comprising the record. The record and therefore the image may be photographic or electronic. The term "image" may thus refer, for example, to an  
30       observable effect in a set of intensity data, for example a table or other stored record of intensity values: the term is not confined to a visual context. The recording medium may comprise a two-dimensional pixilated detector, e.g. an electronic detector such as

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a charge-coupled device (CCD) array.

The irradiating means preferably includes a source of x-rays of diameter 20 micron or less, where diameter refers to the full width of intensity distribution of the source at half maximum intensity. The apparatus may advantageously further include a suitable stage or holder for samples containing the internal boundary being imaged.

The penetrating radiation, e.g. x-ray radiation, may be polychromatic and is preferably in the hard x-ray range, i.e. in the range 1 keV to 1 MeV.

10

The separation of the boundary and the detecting means is preferably selected to enhance the resolution of the image. For example, it has been observed that a sharper image, i.e. one with better contrast, is achieved by increasing separation. For instance contrast is improved at least for a separation of about 1 m relative to a separation of 0.4 m. This may partly be because background noise is diminished with increasing separation but the intensity variation effect arising from the change in the local direction of propagation is substantially preserved.

The term "lateral spatial coherence" herein refers to the correlation of the complex amplitudes of waves between different points transverse to the direction of propagation of the waves. Lateral spatial coherence is said to occur when each point on a wavefront has a direction of propagation which does not change over time. In practice, high lateral spatial coherence may, for example, be achieved by using a source of small effective size or by observing the beam at a large distance from the source. For example, for 20 keV x-rays a source size of 20  $\mu\text{m}$  diameter or less would typically be appropriate. The smaller the source size the better for the purposes of this invention, provided total flux from the source is sufficient. Lateral spatial coherence may need to be preserved by careful selection of the x-ray window of the source, e.g. such that it is of highly uniform thickness and homogeneity.

30

Preferred embodiments of the present invention are hereinafter described, by way of example only, with reference to the accompanying Figures, in which:

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Figure 1 is a diagram, presented in three parts for purposes of illustration, showing a circular cross-section object being irradiated by a parallel beam;

Figure 2 is a diagram of a circular cross-section object being irradiated by a polychromatic beam and the intensity of the phase-contrast image produced;

5 Figure 3 is a diagram of an x-ray optics configuration according to an embodiment of the invention; and

Figures 4 and 5 are x-ray images of various boundaries derived in accordance with the invention, as subsequently detailed herein.

10 It is first now proposed to outline the mathematical basis of the present invention.

Variations in thickness and x-ray refractive index,  $n(\lambda) = 1 - \delta(\lambda) - i\beta(\lambda)$ , of a sample will invariably lead to a change in the shape of an x-ray wavefront on passing  
15 through the sample. The real component  $1 - \delta(\lambda)$  of  $n$  relates to the degree of refraction and the imaginary component  $-i\beta(\lambda)$  relates to the degree of absorption. More specifically, for a single element substance

$$\delta(\lambda) = \frac{r_o \lambda^2}{2\pi} N_o f_R \quad (1)$$

$$\beta(\lambda) = \frac{\lambda}{4\pi} \mu(\lambda) \quad (2)$$

where  $\mu(\lambda)$  is the linear absorption coefficient,  $r_o$  is the classical radius of an electron,  $N_o$  is the number of atoms per unit volume and  $f_R$  is the real part of the atomic  
20 scattering factor at zero scattering angle. The coefficient  $\delta$  is proportional to  $\lambda^2$  and  $\beta$  is proportional to  $\lambda^4$  and also  $\lambda$  is proportional to  $1/\text{energy}$  of the x-ray photon emitted from the source.

The magnitude of the wavefront distortions is related to the gradient of the phase  
25 variations transverse to the direction of propagation of the wavefront. In the geometrical optics approximation, the phase difference,  $\phi$ , for a ray path through an object is proportional to the integral of the decrement of the real part of the refractive index,  $\delta$ ,

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along that ray path. For the coordinate system illustrated in Figure 1 this can be expressed generally as

$$\phi(x,z) = k \int_0^z \{n(x,z') - 1\} dz' \quad (3)$$

where  $k$  is equal to  $2\pi/\lambda$ . The angular deviation  $\Delta\alpha$  of the local scattered wavevector from that of the local incident wavevector is proportional to the gradient of the phase difference in the direction perpendicular to the local incident wavevector. The word "local" refers to a point  $(x,y,z)$  on the wavefront. Mathematically the local scattered wavevector can be written for the coordinate system illustrated in Figure 1 as

$$s(x,y,z) = \left( \frac{\partial\phi}{\partial x}, \frac{\partial\phi}{\partial y}, k \right) \quad (4)$$

where  $s(x,y,z)$  is the normal to the wavefront at point  $(x,y,z)$  and the above relationship is valid in the paraxial approximation when  $(\partial\phi/\partial x)^2 + (\partial\phi/\partial y)^2 \ll k^2$ . The angular deviation  $\Delta\alpha$  can be expressed as

$$\Delta\alpha = \frac{1}{k} \frac{\partial\phi(x,z)}{\partial x} = \int_0^z \left\{ \frac{\partial n(x,z')}{\partial x} - 1 \right\} dz' \quad (5)$$

The angular deviation  $\Delta\alpha$  is therefore dependent on a refractive index variation perpendicular to a propagation wavevector, and the amount of deviation depends on the length over which the variation occurs in the direction of the wavevector, e.g. the thickness of a sample.

To illustrate the nature of the effect, consider the case of a spherical object,  $\Omega$ , of refractive index  $n_M$  embedded in a medium of refractive index  $n_0 = 1$ , as illustrated in Figures 1 and 2.

20

The x-ray optical path length differences through the sample relative to through a vacuum lead to a phase difference  $\phi(x)$  and hence to a phase gradient  $\partial\phi/\partial x$  in the direction (Figure 1) transverse to the local direction of propagation. The phase difference between ray 1 which passes through the object  $\Omega$  parallel to the z-axis at



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constant distance from it and the reference ray 0 is:

$$\phi(x,y) = \frac{2\pi}{\lambda} \int_{-z(x,y)}^0 \delta(\lambda) dt = \frac{2\pi}{\lambda} \delta(\lambda) z(x,y), \quad (6)$$

where  $z(x,y)$  is the length of the intersection of ray 1 with  $\Omega$  and

$$z(x,y) = 2\sqrt{R^2 - x^2 - y^2}, \quad (7)$$

and  $R$  is the radius of  $\Omega$  and  $\delta$  is the decrement of refractive index coefficient. Mathematically, for a circular sectioned object in the  $x$ - $z$  plane, the expression for  
 5  $\partial\phi/\partial x$  and the angular deviation  $\Delta\alpha$  between an incident ray and the corresponding refractive ray for a given  $x$  is:

$$\begin{aligned} \Delta\alpha &= \frac{1}{k} s(x,y,z) \\ &= \frac{\lambda}{2\pi} \frac{\partial\phi}{\partial x} \\ &= -2\delta(\lambda) \left[ \frac{x}{\sqrt{R^2 - x^2}} \right]. \end{aligned} \quad (8)$$

In equation (8),  $\delta(\lambda)$  is slowly varying and it can readily be seen that the phase gradient diverges at  $x = \pm R$ , where the rays can deviate by very large angles from the optic axis. In these limits, the angular deviations of the scattered beams can be very large and lead  
 10 to an observable loss in intensity  $I$  in the corresponding forward direction, the position of which is independent of wavelength, as shown in Figure 2 for a polychromatic beam B. The decrement of refractive index coefficient,  $\delta$ , is typically of order  $10^{-5}$  to  $10^{-6}$  for light elements and hard x-rays but nevertheless the deviation angle  $\Delta\alpha$  may be quite large when  $x$  is close to  $\pm R$ , i.e. at the boundary of the sample or at an internal  
 15 boundary feature.

The nature of the contrast obtained under different conditions of source size, object-source distance and object-image distance, and also the spectral distribution of the source need to be considered. A further consideration affecting contrast is the  
 20 degree of modification of the wavefront introduced by the object.

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For the plane-wave case, to help understand the role of these factors on contrast in image formation, we can to a first approximation use the formula derived by Cowley (J.M. Cowley, "Diffraction Physics", 2nd Ed., p.60, North Holland, 1981) for the Fresnel diffraction contrast from a phase object. According to this formal, for a one-dimensional phase object producing a phase change,  $\phi(x)$ , under plane-wave illumination with wavelength  $\lambda$ , the intensity distribution at a distance  $R_2$  from the object is given by

$$I(x) = 1 + \frac{R_2 \lambda}{2\pi} \phi''(x) \quad (9)$$

which is valid to first order in the quantity  $(R_2 \lambda / 2\pi) \phi''(x)$ , assumed small. From this apparently simple formula, one can draw some significant conclusions, namely:

- i) the contrast varies directly with  $R_2$ ,
- ii) the structure of the image is  $\lambda$ -independent. Only the contrast is affected. For a polychromatic source one would simply replace  $\lambda$  in the formula by a spectrally weighted sum.

To get some feeling for the range of validity of the above formula for the present x-ray case, let us suppose there is an object feature for which the phase transmitted by the object varies by 1 radian over a lateral distance of 10 microns. Then  $\phi'' \sim 10^{10} \text{m}^{-2}$ , and for  $\lambda \sim 1\text{\AA}$ ,  $R_2 \sim 1\text{m}$ , we see that  $(R_2 \lambda / 2\pi) \phi''(x) \leq 1$ . Thus the formula should be valid even for small phase objects or reasonably rapid variations in phase. However, for very sharp edges or changes of slope, such as are often used in calculations of artificial test objects (e.g. fibres),  $\phi''$  may become too large (even infinite), so the formula breaks down. But even in these cases the general form of the image (a black/white line from a sharp step object) is reproduced but not the subsidiary fringes typical of diffraction from such discontinuities. On the other hand, and probably of more practical significance, we see that for smaller  $\phi''(x)$ , i.e. larger features with less rapid lateral variation, the contrast will be low, and may well limit the practical visibility.

A more exact mathematical treatment of this type of imaging with plane-waves

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has recently been carried out in terms of Fresnel diffraction (P. Cloetens, R. Barrett, J. Baruchel, J.P. Guigay and M. Schlenker, J. Phys. D.: Appld. Phys., 1996 29, 133-46; J.P. Guigay, Optik, 1977 49, 121-5). Their treatment gives the same equation as presented above to first order. However the more accurate treatment leads to the  
5 conclusion that the maximum contrast for a spatial frequency  $u$  occurs when  $2 \lambda R_2 u^2 = 1$ , at least for the normal range of conditions expected in phase-contrast radiography. The spatial frequency  $u$  relates to the structure of the object being imaged, where  $u$  equals  $1/A$  where  $A$  is the spatial period of a Fourier component of the imaged object.

10        These treatments all refer to illumination with an ideal plane-wave. Any divergence in the beam will blur the image by an amount proportional to  $R_2$  (in this respect behaving in the same way as in conventional radiography). The above authors (Cloetens et al.) then show that the overall optimum  $R_2$ , taking into account both contrast and resolution is given by

$$R_2 \leq 2 \lambda / \alpha^2 \quad (10)$$

15        where  $\alpha = s/R_1$  is the angle subtended by the source at the object and relates to the (almost) plane-wave case. It should be noted that Cloetens et al. specifically prescribe the need for a highly monochromatic source of x-rays and consider only the plane-wave case in contradistinction to the preferred embodiments described herein.

20        As pointed out, the treatments above relate specifically to the plane-wave case whereas we are principally concerned with the spherical-wave case which more closely relates to convention radiography. To help understand the spatial-wave case, we now consider the relationship between the two which can be usefully established via a simple analysis of the Fresnel-Kirchhoff expression for imaging an object with a point source  
25 at a distance  $R_1$  from the object (the spherical-wave case). This shows that there is a simple relationship for the spherical-wave case involving terms of the plane-wave case but with a modified object to image distance  $R'$ , such that

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$$\frac{1}{R'} = \frac{1}{R_1} + \frac{1}{R_2} \quad (11)$$

and with the image magnified by  $(R_1 + R_2)/R_1$ . From simple geometrical arguments, based on ray optics, it appears that loss of contrast or resolution due to source size will not be a problem in the spherical-wave case as both the image and the source size are magnified, the latter by  $R_2/R_1$  which asymptote to the same factor for large  $R_2$ . The factor affecting contrast for the spherical-wave case is that (for the range of energies and spatial resolutions relevant for radiography)  $2 \lambda R_2 (1 + R_2/R_1) u^2$  should be large (but is typically less than 1). This expression may be large because  $R_2$  is large, or  $\lambda$  large or the spatial frequency,  $u$ , is large. As an illustration, for practical radiographic purposes the following values might serve as being indicative  $\lambda = 0.2 \text{ \AA}$ ;  $u \leq 2 \times 10^5$  (corresponding to a spatial period of 20 micron or more) so that  $R_2 \approx 2.5 \text{ m}$  (assuming  $R_2/R_1 = 3$ , say) would give maximum contrast for the highest spatial frequency. Larger values of  $R_2$  would be appropriate for maximum contrast of lower spatial frequencies.

It may be noted that the function  $\phi''$  will tend to enhance the edges and boundaries of a phase object in an image. If there is also an absorptive component of the object it will, at least to first order, add directly to the image contrast (e.g. see Equation 7 in Guigay, 1977). The present technique could complement and enhance the usual radiological image, as well as yielding new information. It may also be noted that proper treatment of the contrast in an image involving differential phase-contrast (involving the Laplacian of  $\phi$ ) requires numerical processing of the image via, for example, solution of the transport of intensity equations (see T.E. Gureyev, A. Roberts and K. Nugent, Journal of Optical Society of America, Vol. A12, pp.1932 and pp.1942, 1995 incorporated herein by reference) in order to retrieve the phase,  $\phi(x)$ .

We turn now to practical arrangements for applying the concept arising from these determinations. In a first embodiment (Figure 3), there is a source S of high spatial coherence and an x-ray imaging detector D, for example film, photostimulable phosphor plates (e.g. Fuji Image Plates), or a two-dimensional electronic detector. Regions of sharp refractive index variation transverse to the direction of propagation,

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or thickness variation in the direction of propagation, can lead to a significant change in the local direction of propagation of the wavefront passing through those regions. Thus a spherical wavefront W1 emanating from the point source S becomes distorted to W2 on passing through the object O. By recording the intensity of the wavefront at  
5 a sufficient distance from the sample, intensity variations due to sharp refractive index and thickness variations in the sample may be detected and their location recorded in an image. This corresponds to a form of differential phase-contrast imaging. The location of the imaging detector is chosen such that the spatial resolution of the detector is sufficient to resolve the intensity differences arising from the severe distortions of the  
10 wavefront and to optimise contrast, as described above, subject to practical considerations.

Typically, the sharp gradients in refractive index or thickness will be imaged as sharp losses or rapid variation in intensity at corresponding points in the image. This  
15 feature of intensity loss or rapid variation at a given point in the image is essentially independent of wavelength and can therefore lead to very sharp contrast variations in the image even when a polychromatic source is used.

This configuration has the feature that for a circular source distribution, the  
20 spatial resolution in the image is the same for both directions and is essentially determined by the source size. It also has the advantage that considerable magnification of the image is possible and so recording media such as Fuji Image Plates may be used which have many desirable properties such as wide dynamic range and high sensitivity but not high spatial resolution.

25

In addition to the source and detector involved in this configuration, a high resolution angular analyser may be inserted between the sample and the detector. The high resolution angular analyser might for example be a suitably curved crystal in Laue geometry with curvature chosen for some appropriate characteristic wavelength of the  
30 source. This variation in the method is aimed at resolving weaker variations in refractive index and thickness of the sample than are observable with the first described configuration.

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It may be noted that a very substantial magnification of the image is possible so that very high spatial resolution in the image may be achieved even with much lower spatial resolution detectors such as Fuji Image Plates. Also it may be noted that since the method of image formation is essentially independent of x-ray energy, the sources  
5 can be operated at high tube voltage and so lead to lower absorbed dose to the sample, which is important in clinical applications.

Some examples of phase-contrast images recorded using the aforementioned technique are illustrated in Figures 4 and 5. Figure 4 shows an image of the edge of  
10 a 10 $\mu$ m plastic film which is the same as that used in Davis, Gao, Gureyev, Stevenson and Wilkins (Phys. Rev. Letters, 1995, Vol. 74, p. 3173) and corresponds to a pure phase object. Figure 5 shows images of an air bubble and glass fibres in a polymer matrix based on a similar sample to that reported in Davis, Gao, Gureyev, Stevenson and Wilkins (Nature Vol. 373 pp. 595-8, 1995) and corresponds to an almost pure phase  
15 object. In each case clear additional contrast can be seen over that expected for a normal absorption-contrast image. In particular, in Figure 4 the edge of the film is clearly visible as a black/white contrast feature as also are the edges of the bubbles and the fibres. The source used was a nominal 10 $\mu$ m diameter microfocus source (Kevex Model PXS) with Cu anode operated at 40 kV. For Figure 4 the source to sample and  
20 sample to film distances were both 700 mm while for Figure 5 the corresponding distances were 120 mm and 1000 mm, respectively. It should be noted that contrast in the present instances is visible almost entirely due to the high spatial coherence of the source. The contrast is primarily an intensity loss contrast and in that sense resembles normal absorption but is different in that it represents an intensity loss due to refractive  
25 scattering (or Fresnel diffraction) at the object boundaries as shown by equation (8). A normal fine focus source of diameter 0.1 mm would have a projected size of approximately the length of the 0.1 mm scale bar shown on the photographs and so largely smear out this contrast.

30 To provide a comparison of phase-contrast imaging as described herein and standard absorption imaging, the table below sets out the absorption thickness  $t_a$  of a carbon sample required to achieve 65% absorption and the phase thickness  $t_p$  of the

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sample required to achieve a phase change in  $\phi$  of  $2\pi$ , for different source energies  $E$ .

TABLE 1

	E keV	$\lambda(\text{\AA})$	$t_s(\mu\text{m})$	$t_p(\mu\text{m})$
5	50	0.25	435000	133
	12	1	5000	30
	1.2	10	4	3
	0.25	50	1.3	1.2

10 The results in the table illustrate how phase-contrast imaging can be used to image very small objects with high energy sources.

Advantageously, the beam path between sample and detector may involve evacuated tubes with x-ray transparent windows or similar means to reduce the effects  
15 of air scattering making sure that their optical quality is such that they do not have a detrimental effect on the coherence of the x-ray beam.

The present method should be especially well suited to imaging of such features as cracks, voids and delamination effects in various types of materials, since these  
20 features involve maximum differences in x-ray refractive index and the spatial variation can be extremely sharp. To give observable contrast, the source is preferably of a very small effective size, say less than of order  $20\mu\text{m}$ , and the detector is preferably a high resolution imaging detector such as x-ray film or a two-dimensional electronic detector, e.g. a CCD array. The method may also prove useful in significantly enhancing the  
25 contrast of important features in clinical radiography.

The present application outlines some simplified conditions and configurations for differential phase-contrast imaging using penetrating radiation such as hard x-rays, which are particularly aimed at clinical and industrial applications. These new  
30 approaches are more closely related to traditional methods used for absorption-contrast radiography and should be easier to implement than our earlier described methods of the

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aforementioned WO95/05725 and PN5811/95, especially for large areas of irradiation. They should also have considerably shorter exposure times for a given source power than the earlier monochromatic methods since they may use a very wide spectrum from the source.

5

Throughout this specification, unless the context requires otherwise, the word "comprise", or variations such as "comprises" or "comprising", will be understood to imply the inclusion of a stated integer or group of integers but not the exclusion of any other integer or group of integers.

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## CLAIMS:

1. A method of obtaining an image of a boundary of an object, said boundary representing a refractive index variation, said method including:
  - 5 irradiating said boundary with penetrating radiation having high lateral spatial coherence and a propagation component transverse to said refraction index variation; and receiving at least a portion of said radiation on an image plane so as to form said image, said radiation having been refracted by said boundary such that said boundary is represented on said image by a corresponding intensity variation.
- 10 2. A method as claimed in claim 1, including separating the boundary and said image plane by a distance to enhance the contrast between part of said image corresponding to said intensity loss and the remainder of said image.
- 15 3. A method as claimed in claim 2, wherein said distance is greater than or equal to 0.3 m.
4. A method as claimed in claim 2, wherein said distance is greater than or equal to 0.7 m.
- 20 5. A method as claimed in claim 1, wherein the extent of refraction of said radiation depends on the length said refractive index variation is maintained at said boundary in the direction of said propagation component.
- 25 6. A method as claimed in claim 1, wherein said radiation is x-ray radiation having energy in the range 1 keV to 1 MeV.
7. A method as claimed in claim 1, wherein said radiation is polychromatic x-ray radiation.
- 30 8. A method as claimed in claim 1, including generating said radiation with a source less than or equal to 20  $\mu\text{m}$  in diameter.

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9. A method as claimed in claim 1, wherein said intensity variation is sharp and localised.
10. An apparatus for obtaining an image of a boundary of an object, said boundary  
5 representing a refractive index variation, said apparatus including:  
a source for irradiating said boundary with penetrating radiation having high lateral spatial coherence and a propagation component transverse to said refraction index variation; and  
a detector for receiving at least a portion of said radiation so as to form said  
10 image, said radiation having been refracted by said boundary such that said boundary is represented on said image by a corresponding intensity variation.
11. An apparatus as claimed in claim 10, including having a separation distance  
15 between said boundary and said detector to enhance the contrast between part of said image corresponding to said intensity loss and the remainder of said image.
12. An apparatus as claimed in claim 11, wherein said distance is greater than or equal to 0.3 m.
- 20 13. An apparatus as claimed in claim 11, wherein said distance is greater than or equal to 0.7 m.
14. An apparatus as claimed in claim 10, wherein the extent of refraction of said radiation depends on the length said refractive index variation is maintained at said  
25 boundary in the direction of said propagation component.
15. An apparatus as claimed in claim 10, wherein said source generates x-ray radiation with energy in the range 1 keV to 1 MeV.
- 30 16. An apparatus as claimed in claim 10, wherein said source generates polychromatic x-ray radiation.

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17. An apparatus as claimed in claim 10, wherein said source has a diameter less than or equal to 20  $\mu\text{m}$ .
18. An apparatus as claimed in claim 10, wherein said intensity variation is sharp  
5 and localised.
19. A method of deriving a phase-contrast record of an internal boundary having a sharp refractive index variation or defined by a thickness variation, comprising:  
irradiating the boundary with penetrating radiation having a propagation direction  
10 such that there is a significant component of the propagation vector transverse to the direction of said refractive index variation or in the direction of said thickness variation, and further having a lateral spatial coherence sufficiently high for the variation in refractive index or thickness to cause a detectable change in the local direction of propagation of the radiation wavefront at the boundary; and  
15 detecting and recording at least a portion of said radiation after it has traversed said boundary in a manner whereby an effect of said change in the local direction of propagation is observable and thereby recorded as a local diminution or rapid variation of intensity of the radiation which thereby substantially images the boundary.
20. 20. A method as claimed in claim 19, wherein said radiation is polychromatic x-ray radiation.
21. A method as claimed in claim 19, wherein said radiation is x-ray radiation having energy in the range 1 keV to 1 MeV.  
25
22. A method as claimed in claim 19, including irradiating said boundary with a source of x-rays having a diameter less than or equal to 20  $\mu\text{m}$ .
23. A method as claimed in claim 19, including separating said boundary and the  
30 position of detecting said portion of said radiation by a distance which enhances the resolution of an image comprising the record of said local diminution or rapid variation of intensity.

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24. A method as claimed in claim 23, wherein said distance is greater than or equal to 0.3 m.
25. A method as claimed in claim 23, wherein said distance is greater than or equal  
5 to 0.7 m.
26. An apparatus for deriving a phase-contrast record of an internal boundary having a sharp refractive index variation or defined by a thickness variation, comprising:  
means to irradiate the boundary with x-ray radiation having a propagation  
10 direction such that there is a significant component of the propagation vector transverse to the direction of said refractive index variation or in the direction of said thickness variation, and further having a lateral spatial coherence sufficiently high for the variation in refractive index or thickness to cause a detectable change in the local direction of propagation of the radiation wavefront at the boundary; and  
15 means to detect and record at least a portion of said radiation after it has traversed said boundary in a manner whereby an effect of said change in the local direction of propagation is observable and thereby recorded as a local diminution or rapid variation of intensity of the radiation which thereby substantially images the boundary.  
20
27. An apparatus as claimed in claim 26, wherein said radiation is polychromatic x-ray radiation.
28. An apparatus as claimed in claim 26, wherein said radiation is x-ray radiation  
25 having energy in the range 1 keV to 1 MeV.
29. An apparatus as claimed in claim 26, wherein said means to irradiate is a source of x-rays having a diameter less than or equal to 20  $\mu\text{m}$ .
30. An apparatus as claimed in claim 26, wherein said boundary and the position of detecting said portion of said radiation are separated by a distance which enhances the resolution of an image comprising the record of said local diminution of intensity.

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31. An apparatus as claimed in claim 30, wherein said distance is greater than or equal to 0.3 m.
32. An apparatus as claimed in claim 30, wherein said distance is greater than or  
5 equal to 0.7 m.
33. A method of obtaining an image of a boundary of an object, said boundary representing a refractive index variation, said method including:  
irradiating said boundary with penetrating radiation having high lateral spatial  
10 coherence and a propagation component transverse to said refraction index variation; and  
receiving at least a portion of said radiation on an image plane so as to form said image, said radiation having been Fresnel diffracted by said boundary such that said boundary is represented on said image by a corresponding intensity variation.
- 15 34. An apparatus for obtaining an image of a boundary of an object, said boundary representing a refractive index variation, said apparatus including:  
a source for irradiating said boundary with penetrating radiation having high lateral spatial coherence and a propagation component transverse to said refraction index variation; and  
20 a detector for receiving at least a portion of said radiation so as to form said image, said radiation having been Fresnel diffracted by said boundary such that said boundary is represented on said image by a corresponding intensity variation.
35. A method of determining the phase of an image, including processing  
25 phase-contrast image data of said image.
36. A method as claimed in claim 35, wherein said processing is based on Maxwell's equations for electromagnetic radiation.
- 30 37. A method as claimed in claim 36, wherein said equations are the transport of intensity equations.

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38. A method of determining the phase of an image, including processing an image obtained using a method as claimed in any one of claims 1 to 9 or 19 to 23.

39. A method of determining the phase of an image as claimed in claim 38, wherein  
5 said processing is based on Maxwell's equations for electromagnetic radiation.

40. A method of determining the phase of an image as claimed in claim 39, wherein said equations are the transport of intensity equations.

## AMENDED CLAIMS

[received by the International Bureau on 29 July 1996 (29.07.96); original claims 35-37 cancelled; original claims 1, 2, 10, 11, 19, 23, 26, 30, 33 and 34 amended; new claims 41 and 42 added; remaining claims unchanged (6 pages)]

1. (Amended) A method of obtaining an image of a boundary of an object, said boundary representing a refractive index variation, said method including:
  - 5 irradiating said boundary with penetrating radiation having high lateral spatial coherence and a propagation component transverse to said refractive index variation; and receiving at least a portion of said radiation on an image plane so as to form said image, said radiation having been refracted by said boundary such that said boundary is represented on said image by a corresponding intensity variation in said image.
- 10 2. (Amended) A method as claimed in claim 1, including separating the boundary and said image plane by a distance to enhance the contrast of said intensity variation.
3. A method as claimed in claim 2, wherein said distance is greater than or equal to  
15 0.3 m.
4. A method as claimed in claim 2, wherein said distance is greater than or equal to 0.7 m.
- 20 5. A method as claimed in claim 1, wherein the extent of refraction of said radiation depends on the length said refractive index variation is maintained at said boundary in the direction of said propagation component.
6. A method as claimed in claim 1, wherein said radiation is x-ray radiation having  
25 energy in the range 1 keV to 1 MeV.
7. A method as claimed in claim 1, wherein said radiation is polychromatic x-ray radiation.
- 30 8. A method as claimed in claim 1, including generating said radiation with a source less than or equal to 20  $\mu\text{m}$  in diameter.

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9. A method as claimed in claim 1, wherein said intensity variation is sharp and localised.
10. (Amended) An apparatus for obtaining an image of a boundary of an object, said  
5 boundary representing a refractive index variation, said apparatus including:  
a source for irradiating said boundary with penetrating radiation having high lateral spatial coherence and a propagation component transverse to said refractive index variation; and  
a detector for receiving at least a portion of said radiation so as to form said image,  
10 said radiation having been refracted by said boundary such that said boundary is represented on said image by a corresponding intensity variation in said image.
11. (Amended) An apparatus as claimed in claim 10, including having a separation distance between said boundary and said detector to enhance the contrast of said intensity  
15 variation.
12. An apparatus as claimed in claim 11, wherein said distance is greater than or equal to 0.3 m.
- 20 13. An apparatus as claimed in claim 11, wherein said distance is greater than or equal to 0.7 m.
14. An apparatus as claimed in claim 10, wherein the extent of refraction of said radiation depends on the length said refractive index variation is maintained at said  
25 boundary in the direction of said propagation component.
15. An apparatus as claimed in claim 10, wherein said source generates x-ray radiation with energy in the range 1 keV to 1 MeV.
- 30 16. An apparatus as claimed in claim 10, wherein said source generates polychromatic x-ray radiation.



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17. An apparatus as claimed in claim 10, wherein said source has a diameter less than or equal to 20  $\mu\text{m}$ .

18. An apparatus as claimed in claim 10, wherein said intensity variation is sharp and  
5 localised.

19. (Amended) A method of deriving a phase-contrast record of an internal boundary representing a sharp refractive index variation, comprising:

10 irradiating the boundary with penetrating radiation having a propagation direction such that there is a significant component of the propagation vector transverse to the direction of said refractive index variation, and further having a lateral spatial coherence sufficiently high for the variation in refractive index to cause a detectable change in the local direction of propagation of the radiation wavefront at the boundary; and

15 detecting and recording at least a portion of said radiation after it has traversed said boundary in a manner whereby an effect of said change in the local direction of propagation is observable and thereby recorded as a local diminution or rapid variation of intensity of the radiation which thereby substantially images or detects the boundary.

20 20. A method as claimed in claim 19, wherein said radiation is polychromatic x-ray radiation.

21. A method as claimed in claim 19, wherein said radiation is x-ray radiation having energy in the range 1 keV to 1 MeV.

25 22. A method as claimed in claim 19, including irradiating said boundary with a source of x-rays having a diameter less than or equal to 20  $\mu\text{m}$ .

23. (Amended) A method as claimed in claim 19, including separating said boundary and the position of detecting said portion of said radiation by a distance which enhances  
30 the contrast and/or resolution of the part of an image comprising the record of said local diminution or rapid variation of intensity.

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24. A method as claimed in claim 23, wherein said distance is greater than or equal to 0.3 m.

25. A method as claimed in claim 23, wherein said distance is greater than or equal  
5 to 0.7 m.

26. (Amended) An apparatus for deriving a phase-contrast record of an internal boundary representing a sharp refractive index variation, comprising:

means to irradiate the boundary with x-ray radiation having a propagation  
10 direction such that there is a significant component of the propagation vector transverse to the direction of said refractive index variation, and further having a lateral spatial coherence sufficiently high for the variation in refractive index to cause a detectable change in the local direction of propagation of the radiation wavefront at the boundary;  
and

15 means to detect and record at least a portion of said radiation after it has traversed said boundary in a manner whereby an effect of said change in the local direction of propagation is observable and thereby recorded as a local diminution or rapid variation of intensity of the radiation which thereby substantially images or detects the boundary.

20 27. An apparatus as claimed in claim 26, wherein said radiation is polychromatic x-ray radiation.

28. An apparatus as claimed in claim 26, wherein said radiation is x-ray radiation having energy in the range 1 keV to 1 MeV.

25

29. An apparatus as claimed in claim 26, wherein said means to irradiate is a source of x-rays having a diameter less than or equal to 20  $\mu\text{m}$ .

30. (Amended) An apparatus as claimed in claim 26, wherein said boundary and the  
30 position of detecting said portion of said radiation are separated by a distance which enhances the contrast and/or resolution for part of an image comprising the record of said

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local diminution or rapid variation of intensity.

31. An apparatus as claimed in claim 30, wherein said distance is greater than or equal to 0.3 m.

5

32. An apparatus as claimed in claim 30, wherein said distance is greater than or equal to 0.7 m.

33. (Amended) A method of obtaining an image of a boundary of an object, said  
10 boundary representing a refractive index variation, said method including:

irradiating said boundary with penetrating radiation having high lateral spatial coherence and a propagation component transverse to said refractive index variation; and

receiving at least a portion of said radiation on an image plane so as to form said image, said radiation having been Fresnel diffracted by said boundary such that said  
15 boundary is represented on said image by a corresponding intensity variation in said image.

34. (Amended) An apparatus for obtaining an image of a boundary of an object, said boundary representing a refractive index variation, said apparatus including:

20 a source for irradiating said boundary with penetrating radiation having high lateral spatial coherence and a propagation component transverse to said refractive index variation; and

a detector for receiving at least a portion of said radiation so as to form said image, said radiation having been Fresnel diffracted by said boundary such that said boundary  
25 is represented on said image by a corresponding intensity variation in said image.

35. (Deleted)

36. (Deleted)

30

37. (Deleted)

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38. A method of determining the phase of an image, including processing an image  
obtained using a method as claimed in any one of claims 1 to 9 or 19 to 23.

39. A method of determining the phase of an image as claimed in claim 38, wherein  
5 said processing is based on Maxwell's equations for electromagnetic radiation.

40. A method of determining the phase of an image as claimed in claim 39, wherein  
said equations are the transport of intensity equations.

10 41. (New) A method as claimed in claim 1, wherein said radiation is generated by and  
provided from a source to said boundary without Bragg diffraction.

42. (New) An apparatus as claimed in claim 10, wherein said radiation is generated  
by and provided from a source to said boundary without Bragg diffraction.

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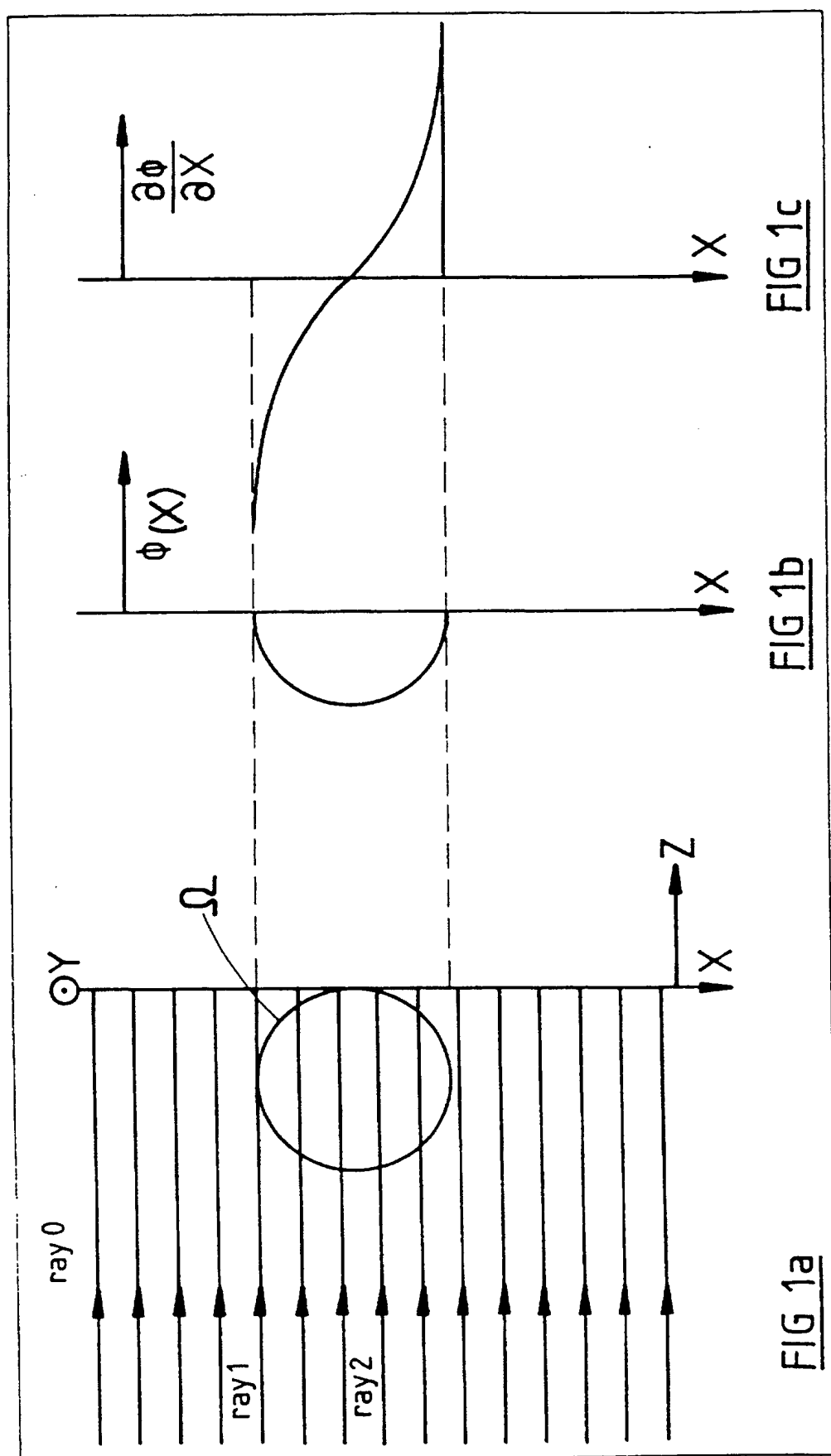
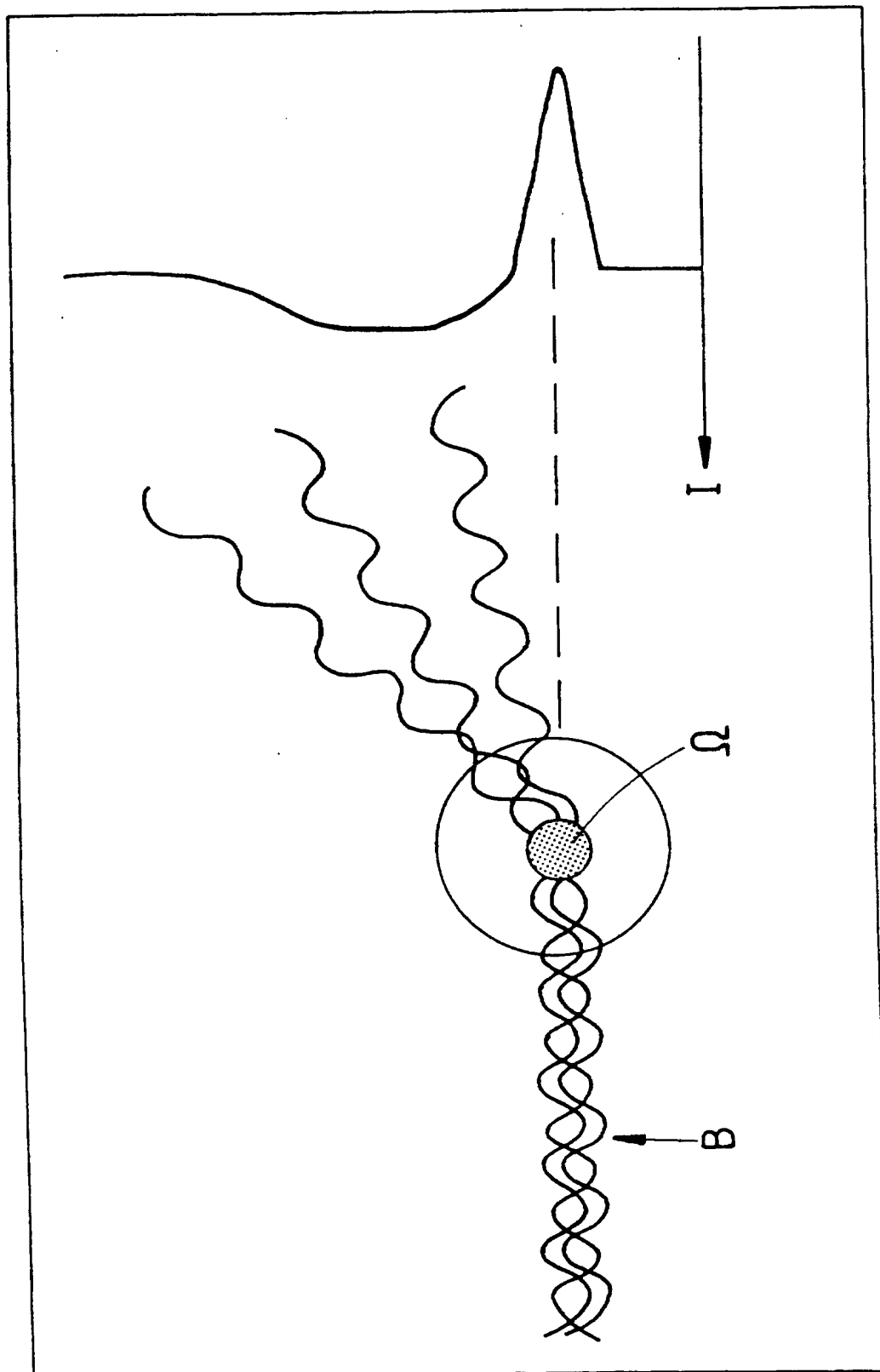


FIGURE 1

FIG 2

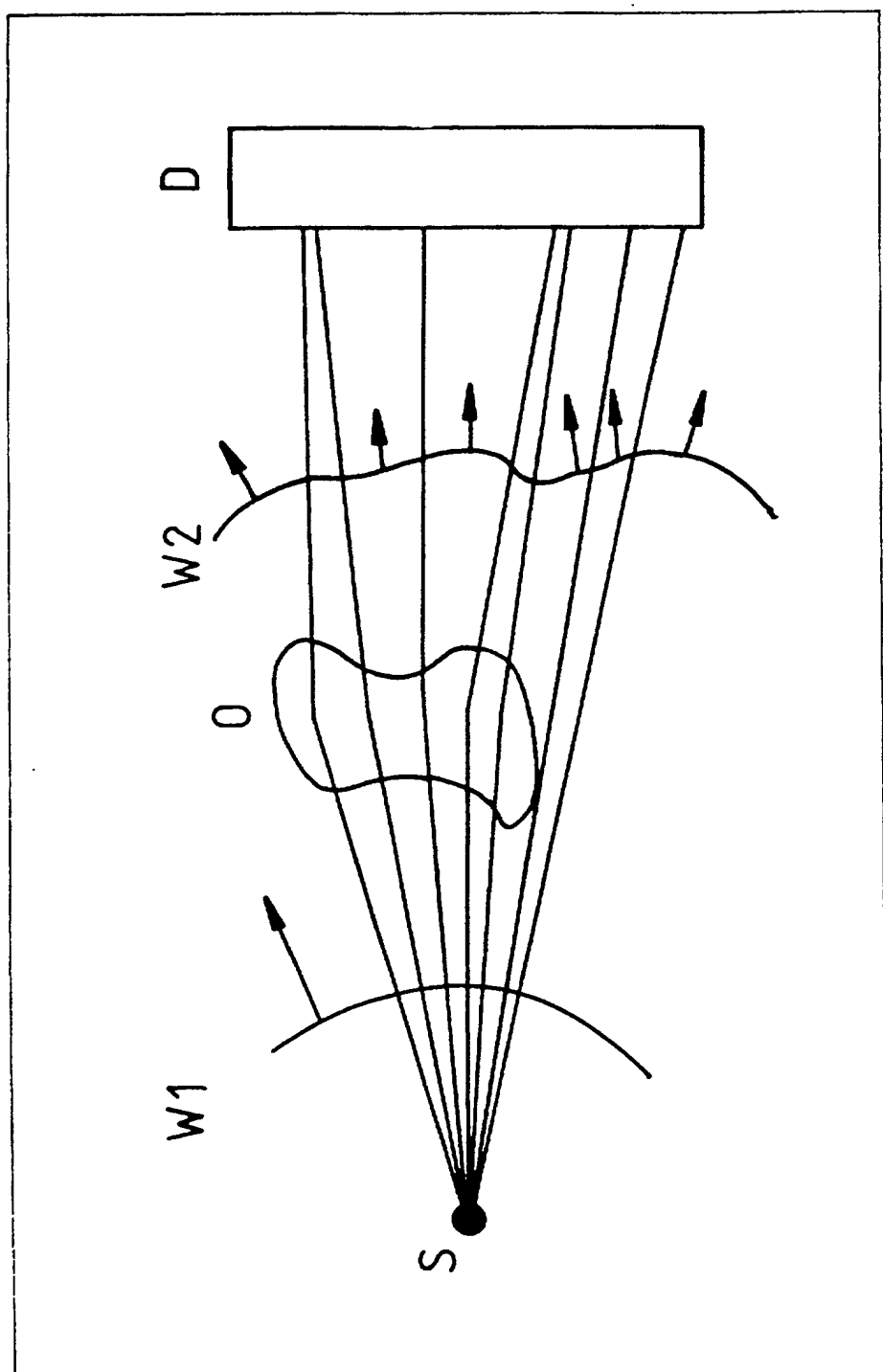


FIG 3

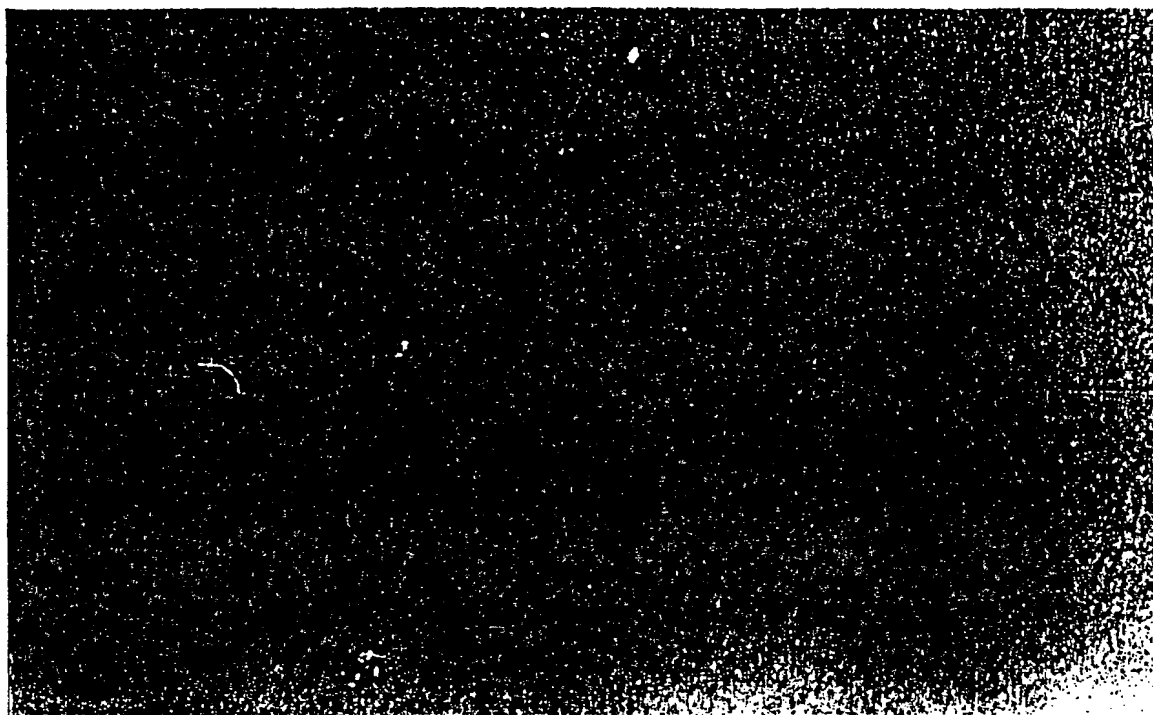
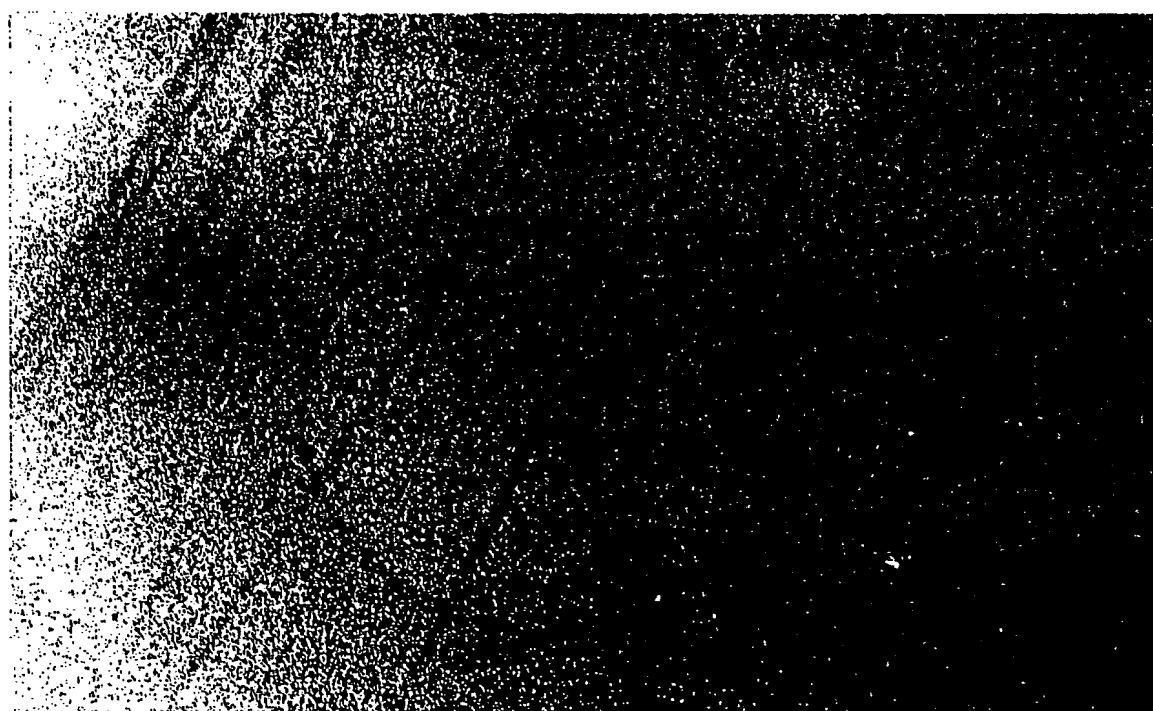


FIGURE 4



0.1 mm

FIGURE 5



# INTERNATIONAL SEARCH REPORT

International Application No.  
PCT/AU 96/00178

<b>A. CLASSIFICATION OF SUBJECT MATTER</b>		
Int Cl <sup>6</sup> : H05G 1/02, G21K 1/02, G03B 42/02, A61B 6/00		
According to International Patent Classification (IPC) or to both national classification and IPC		
<b>B. FIELDS SEARCHED</b>		
Minimum documentation searched (classification system followed by classification symbols) IPC : as above		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched AU : IPC as above		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) WPAT: JAPIO: INSPEC: MEDLINE (Phase( ) contrast, imag., X( )RAY)		
<b>C. DOCUMENTS CONSIDERED TO BE RELEVANT</b>		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	WO 95/05725 A (CSIRO) 23 February 1995 whole document	35-40 6, 15, 21, 28
Y	US 5319694 A (INGAL et al ) 7 June 1994 Abstract, Figures	1, 10, 19, 26
Y	US 4953188 A (SIEGAL et al) 28August 1990 whole document	1, 10, 19, 26
<input checked="" type="checkbox"/> Further documents are listed in the continuation of Box C <input checked="" type="checkbox"/> See patent family annex		
* Special categories of cited documents: "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier document but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 1 May 1996		Date of mailing of the international search report 9TH MAY 1996.
Name and mailing address of the ISA/AU AUSTRALIAN INDUSTRIAL PROPERTY ORGANISATION PO BOX 200 WODEN ACT 2606 AUSTRALIA Facsimile No.: (06) 285 3929		Authorized officer  DALE SIVER Telephone No.: (06) 283 2196

# INTERNATIONAL SEARCH REPORT

International Application No.

PCT/AU 96/00178

C (Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	"Radiation damage in soft X-ray microscopy of live mammalian cells" (Shinohara et al) from Journal of Microscopy, Vol. 161, pt. 3, pp.463-72, March 1991, Abstract, Table 1 References	6, 15, 21, 28, 35
Y	EP 274155 A (PHILIPS) 13 July 1988 Abstract, Figures, col. 4 lines 23-29	1, 10, 19, 26
Y	US 4200354 A (HOFFMAN) 29 April 1980 whole document	1, 10, 19, 26, 35-40
Y	OPTICS (Hecht/Zajac) 1973, pp. 449, 450 and pp. 474-479)	1, 10, 19, 33-40
A	EP 599361 A (IBM) 1 June 1994	
A	EP 466047 A (HITACHI) 15 January 1992	
A	US 5016267 A (CSIRO) 14 May 1991	

## INTERNATIONAL SEARCH REPORT

International Application No.

**PCT/AU 96/00178**

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report				Patent Family Member			
WO	9505725	AU	74538/94				
US	5319694	EP WO	539608 9221016	JP	6507019	RU	2012872
US	4953188	CH	678663	DE	3819603	JP	2110400
EP	274155	DE US	3777594 4845352	JP	63155114	NL	8603108
US	4200354	CA GB	1031199 1502657	DE JP	2523464 51029149	FR	2284126
EP	599361	JP	6201602	US	5446540		
EP	466047	US	5173928	JP	4348262		
US	5016267	AT EP	89097 322408	AU JP	78077/87 2501338	DE WO	3785763 8801428

